Hydrol. Earth Syst. Sci. Discuss., 9, C274–C285, 2012
www.hydrol-earth-syst-sci-discuss.net/9/C274/2012/

Hydrology and Earth System Sciences Discussions

Interactive comment on "Estimation of future groundwater recharge using climatic analogues and Hydrus-1D" *by* B. Leterme et al.

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Received and published: 9 March 2012

We'd first like to thank Olga Barron for her constructive comments and suggestions. Hereafter we give our reply to her comments, including modifications that we will implement in the final version of the manuscript.

The main comments

1. Future climate projections:

a. The method for future climate projection would require clearer description. This is particularly related to the time line of the projections. Firstly, it may be useful to provide some reasoning why 10,000 timeline is selected. I presume this is due to the reference of nuclear waste disposal, and the needs to align projection with the life-time of possible

contaminants, but I think it will help to provide some statement in this line.

–> The reference to justify the considered time scale was already given in the manuscript ("The time scale of interest is several millennia (Van Geet et al., 2012).") To give additional clarifications, we modify the text as follows: "The time scale of interest is several millennia, considering the long half-life of some radionuclides (i.e. several thousands to tens of thousands of years) contained in LILW-SL and the anticipated lifetime (a few thousands of years) of the near-surface facility (Van Geet et al., 2012)."

b. The author suggested that the GCMs results do not provide the required time scale of the projection (10,000 year); however the selection of the climate type which is likely to replace the current one in Belgium is still based on the GCM projections by 2100. With dynamic changes in climatic condition it is not clear what was the basis for an assumption that significant climatic changes are likely to occur during 100 years (climate type changes from temperate oceanic to subtropical), which may remain unchanged for the following 9,9000 year.

–> We meant that GCM projections are not fit for the purpose of capturing the interannual variability in regional water balance on several millennia. We used GCM projections to define a sequence of climate states over a period of at least 10,000 years. We then explore the possible variability in the soil water balance within each of these climate states separately, using the approach of analogue stations. Yet, we acknowledge that instrumental records from analogue stations are unlikely to include the full range of climate conditions for an individual site during any given climate state (BIOCLIM, 2003).

The selection of the climate type which is likely to replace the current one in Western Europe is not based on the GCM projections until 2100; it is based on GCM projections up to one million years (BIOCLIM, 2003). We modify the text as follows, p.1393: "The BIOCLIM (2003) project studied possible future climate states for the long term accounting for atmospheric CO2, solar and astronomical forcings. The reference sequence of climate states (B4) is Cs/Cr climate until 160,000 years AP, followed by a temperate oceanic climate (DO from 160,000 to 170,000 y AP), then a cold climate without permafrost (EO from 170,000 – 180,000 y AP) and finally again a temperate climate (till 200,000 y AP). Over the period..."

The reference climate evolution selected from BIOCLIM (2003) simulations – B4 scenario of high CO2 emissions – thus remains within the bounds defined by the Cs/Cr subtropical class for the next 10,000 years.

c. The application of a tundra climate data for the analysis without consideration of the permafrost effect on the recharge does not seem to be justifiable, as it effect on water fluxes and their seasonality in soil profile is most profound. There is some reference to this in the text, but it is not clear how meaningful is the result of the analysis for FT climate type.

–> It is true that soil freezing and thawing has an effect on groundwater recharge in the case of a FT climate state, and this is acknowledged in the text (p.1397, l.17-20: "...soil freezing and thawing were not simulated in the present study and these would probably reduce groundwater recharge for analogue stations of the FT class."

In practice, frozen soil can lead to enhanced runoff when snow melts. Therefore, not simulating freeze/thaw processes would tend to overestimate the amount of infiltrating water, as stated in our paper. It is true that for these reasons, in the case of the FT class the seasonality of soil water fluxes is probably not well captured by our simulations, but the main objective of the study is the quantification of average annual groundwater recharge.

We will add the following §to the discussion: "The simulations represent an upper bound of groundwater recharge (by neglecting runoff of snow melt), and the lower bound could be approximated by the difference between this upper bound and the average snowpack accumulation before spring melting (i.e. assuming all snow becomes runoff or evaporates). This gives a lower bound value of $\sim$16 mm groundwater

recharge for Sisimiut, compared to 96 mm when all snow infiltrates. Getting a more precise estimation between these two bounds would require the effect of soil freezing and snow accumulation on soil water flux to be modelled. For example, frozen soil development was shown to be highly dependent on the timing of snowpack accumulation and induced ground isolation (Iwata et al., 2008)."

Iwata, Y., Hayashi, M., and Hirota, T.: Comparison of snowmelt infiltration under different soil-freezing conditions influenced by snow cover, Vadose Zone J. 7(1):79–86, doi:10.2136/vzj2007.0089, 2008

d. The climate data from climate types used for the future projection are selected to reproduce average and extreme climate data. It would be also useful to provide a better characterisation of the meteorological/climatic condition in Dessel: how do they fall within the range of rainfall data within temperate oceanic climate zone? It would be also useful to identify how extreme climate data within temperate climate type may affect recharge estimation.

–> Range of rainfall data within temperate oceanic climate class: there is no criterion about precipitation in the definition of DO climate class following Trewartha (4 to 7 months above 10 °C, and coldest month above 0°C are the only criteria). We modify the text at the beginning of section 2.1 as follows : "The present-day climate of Belgium is defined as a temperate oceanic climate âŤĂ "DO" following the classification of Trewartha (1968). Classification as DO climate type requires 4 to 7 months above 10 °C and the coldest month above 0°C (there is no criterion about precipitation)."

We will add a Table to supplementary material, to provide some idea of climate variability within DO class, and adapt the text at the end of section 2.2: "Table 1 lists the selected climatic analogue stations for simulating the warmer (Cs/Cr) and colder (FT) climate classes. Table XX (in supplementary material) presents average temperature and precipitation for twelve analogue stations of the DO climate class (with the same selection criteria as described above), including Dessel. Dessel is found to have higher annual precipitation than the class average based on these twelve stations (851 mm), and temperature equal to the average (10.3 °C)."

Table XX (see supplement) – Annual temperature and precipitation of a sample of European stations representative of climate variability within the DO class, with the same selection criteria as presented in section 2.2 (sources : IRM-KMI, www.meteo.be; KNMI, www.knmi.nl; Meteofrance, www.climat.meteofrance.com; Met Office, www.metoffice.gov.uk; Met Éireann, www.met.ie).

How extreme climate data affect recharge estimation was considered not particularly relevant for the present study, because we focus on the average, long term groundwater recharge and long-term average groundwater flows and contaminant migration. In this respect the importance of a single extreme event, whether dry or wet, with a long return period is limited. This would of course not be the case for similar studies focusing for example on extreme events of surface runoff in response to climate change.

e. It would be also useful to compare the outcome of this study with the similar studies based on GCM results and their downscaling. It seems that the projected changes in recharge under alternative climate type have a large range (60 mm vrs 314 mm). Is it comparable with GCM-based analysis? The reference to 9% increase in rainfall in northern Europe, stated in the paper, is likely to have some band of projection if more than 1 GCM was used.

–> We cite one recent studies based on GCM and downscaling using RCM in Belgium. We will adapt section 3.1 (after the presentation of results for the Cs/Cr class) by including the following text: "In a study using GCM and RCM downscaling, Goderniaux et al. (2009 estimated the impact of climate change by 2100 on the regional water balance in a Belgian catchment (the Geer basin ∼70 km from Dessel site, chalk aquifer). They applied 6 scenarios derived from combinations of the A2 scenario run on 2 different GCMs with 4 different RCMs for downscaling. Annual mean temperature increase ranges from +3.5 °C to +5.6 °C, and annual precipitation decrease from

−1.9% to −15.3% (with increase in winter and decrease in summer). Groundwater recharge is not explicitely given in the water balance, but their simulations (coupled surface, subsurface and hydrogeological flow) gave the following results for the period 2071-2100 compared to the control period 1961-1990: (i) slight increase of the ratio ETa/precipitation (+2-4%), (ii) decrease of groundwater levels (i.e. decrease of groundwater recharge) and (iii) decrease of surface flow rates (−9 to −33%)."

Goderniaux, P., Brouyère, S., Fowler, H. J., Blenkinsop, S., Therrien, R., Orban, P., and Dassargues, A. : Large scale surface-subsurface hydrological model to assess climate change impacts on groundwater reserves, Journal of Hydrology 373(1-2): 122-138, 2009

2. Recharge estimation: gross recharge vrs net recharge a. It may be useful to introduce a concept of net and gross recharge. As describe in the paper the shallow groundwater in the region lead to the evaporative losses from groundwater itself, and as such the annual "net" recharge would be low or even negative. The gross recharge or the amount of water reaching groundwater table is likely to be high due to the thin unsaturated zone and highly permeable soils. It appears that the paper examine the latter. It would be useful to clarify how important is the effect of climate change on net diffuse recharge in these conditions. Reduction in gross recharge may lead to reduction in evaporative losses and as such may have minimum effect on net recharge. Is it possible to clarify what changes in gross recharge may lead to changes in net recharge?

–> The distinction between gross and net recharge is not necessary for the simulations presented in our paper, because the bottom boundary condition used (eq. (1)) forces a water flux always downwards at the bottom of the soil profile and therefore the gross recharge is effectively equal to the net recharge. This is stated in the 1st §of section 3.3.

3. Clarity of presentation : the paper would benefit from scientific editing, with more

specific comments are given below (the items are marked in the attached manustript)

–> Cf. response to specific comments hereafter. Minor typos/corrections noted only on the manuscript will be taken into account as well.

Abstract (1) I would suggest using past tense

–> Ok

(2) No clear : what current state is referring to here

–> Modify by: "...stations presently experiencing climatic conditions corresponding to a possible future climate state".

(3) It is confusing when the projections of 10,000 year based on 24 year observation record. It would be useful to clarify

–> Modify by: "...this includes giving an estimation of groundwater recharge for the next millennia".

Introduction (4) GCM definition: we commonly use Global Climate Model, rather than "General". Probably it would be useful to check?

–> General circulation model and Global climate model are used interchangeably.

(5) Under the item (b) it would be useful to give references to the previous studies where such method was applied for the future climate projections. Alternatively, if this is the first time this method used, the overall structure of introduction needs to be revised.

–> The references are given further. Text will be modified to bring references (Palutikof and Goodess, 1991; Bechtel SAIC Company, 2004) up front under b).

(6) It is not clear what does this mean "an entire climate state"? Why the meteorological stations are "not optimal in terms of the environmental condition on its site"? What site does this refer to? Editing is required.

–> "An entire climate state" refers to the long-term temporal variability within the climate

states defined should long time series be available. Text modified as follows: "...analogues are restricted to sites with instrumental data; furthermore time series of 30 to 50 years are assumed to be representative of the long-term temporal variability of a given climate state; finally the site conditions of analogue stations that impact their climate will hardly be ever identical to those of the site (here Dessel) they are an analogue for."

(7) It is not clear why the use of 30-50 years observation is more reliable for such projections? The latter in the paper the selection of "future" climate type is still based on the GCM projection within the next 100 years.

–> We do not state that 30-50 y observations are more reliable, but we argue that beyond the usual 2100 predictions the potential advantages of GCMs over an analogue approach are lost due to the high uncertainty in emission scenarios and GCM predictions. On the other hand, we are aware that the climate states used in the analogue approach are based on long-term GCM simulations which are similarly very uncertain! It is thus some hybrid approach that we used: selection of climate states based on GCM predictions, then use analogue stations to get real data for each state. However, the bounding of (broad) climate states is in our opinion more consistent with this uncertainty than deriving 10,000 y weather time series from GCMs. Ultimately the two approaches are complementary, because the latter (GCMs and RCM downscaling) have the potential to underpin the robustness of the former (analogue stations) by including a more mechanistically based approach to obtain input variables or to assess broad consequences of climate change.

(8) Editing is needed: why this scenario can not be excluded? Particularly when other conditions under this scenario (e.g. permafrost) are not included in consideration or discussed based on other published studies.

–> Colder climate cannot be excluded because most of the BIOCLIM scenarios identify colder climate states as a possible future climate at some time in the far future.

Material and methods

(9) Should mention here what is a seasonal rainfall distribution for DO climate type (as it is further compared with Cs and Cr)

–> Classification as DO climate type do not contain criteria regarding precipitation quantity or seasonality: there has to be 4 to 7 months above 10 °C and coldest month above 0°C (see comment 1.d. above).

Seasonality of current DO climate in Dessel is graphically presented in Fig. 2 and can be compared to Gijon and Sisimiut.

(10) As in the main comments: the climate type shift is projected by GCM by 2100, but the target is 10,000 in the future. How the use of 100 years projection is extrapolated to 10,000 years. What does "AD" mean

–> The BIOCLIM projections define the broad-brush long-term climate evolution, and this means evolution from DO into Cr over the next few hundred year after which the climate remains in Cr for a long time. Next, the short-term GCM predictions, i.e until 2100, are used to better constrain what this Cr climate would look like in Western Europe, This information is used to select the climate analogue station. It is then assumed that this Cr climate will remain relatively constant for the entire duration of the evalution (up to 10,000 y).

"AD" means Anno Domini (used before dates after the supposed year Christ was born) and is used to avoid confusion with XX years AP (after present).

Climatic analogue stations (11) This para require editing: the description of the station selection and it relevance to the climate type is not clear

–> We modify the text as follows : "...the two stations displaying the smallest rank deviation from the class annual average temperature and precipitation were arbitrarily selected for model simulation. Besides these two stations, the two stations with the highest and lowest precipitation regimes were also selected to represent extreme cases."

(12) Table 1 : it would be useful to give some indication where Dessel meteorological data sits within the DO climate (close to average, max, min)?

–> The definition of the DO climate considers temperature only (4 to 7 months above 10°C and coldest month above 0°C, no criterion about precipitation). Dessel has 6 months above 10°C. Modification to the text (section 2.1) and Table in supplementary material (cf. comment 1.d above).

(13) The reference is not in correct place in the reference list

–> This is due to the accent on the S and the LaTeX template of HESSD; I'm not sure how to solve that, I will notify the editors.

(14) I am not familiar with soil classification in the region and for me it is not clear what the term "poorly drained" related to, when sandy soil is considered? Does this suggest that the soil is waterlogged? In the modelling described further the lower drainage boundary kept on 3 m would not allow waterlogging. Would this influence the soil properties over the proposed assessment period?

–> There are 9 drainage classes (second letter of the soil profile code) in the Belgian soil classification, from "a" (very dry, "excessive drainage") to "g" (extremely wet, very poor drainage). Zeg thus corresponds to a wet soil profile, with a horizon of reduction ("moderately poor drainage"). The poorly drained is mainly related to its position in the landscape, usually in a depression or near a river alluvium with shallow groundwater. The situation would change if the groundwater is put at 3 m below surface, and we currently assume this will not change its hydraulic properties. Analysis of long-term evolution of soil hydraulic properties and its influence on groundwater recharge was beyond the scope of the present paper; but will be discussed elsewhere (results not yet published).

(15) It may be useful to show the seasonal water table fluctuation range

–> We will add this information at the end of section 2.3: "For the 12 piezometers used to derive the parameters of eq. (1), average annual minimum and maximum water level are 1.2 and 2.1 m, respectively."

Results (16) Table 3 shows the water budget related to recharge modelling results using climate data and under the grass cover (not the water budget of the climate station). Editing is required

–> We propose rephrasing as "...shows the long-term arithmetic average water budget related to groundwater recharge for a grass cover using analogue climatic data."

(17) Should the depth to groundwater for each scenario be added to the table?

–> We will add it as a footnote to the Table: Dessel 2.6 m, Gijon 2.8 m, Sisimiut 4.5m.

(18) The word "record" should be omitted: low precipitation is the driving force, not its record

–> Ok

(19) I am not sure if Figure 1 adds more information than Table 3.

–> It brings information on the seasonality of precipitation and groundwater recharge.

(20) Same comment as in (8)

–> Is it same comment as in (7) ? Then we refer to the response to this comment.

(21) If the paper is going to be present in it current layout, the position of tables and figure 1 should be better aligned with the referenced to them in the text: e.g. Figure 1 in text is mentioned after references to table 3.

–> Ok

(22) The vegetation was modelled with the root zone or 30 cm, while the depth to groundwater within the model was much lower. Is it still "shallow enough for use by vegetation"?

–> We modify the sentence : "...prevents a net negative bottom flux (water supply from the aquifer), but allows groundwater table to fluctuate. For Dessel and Gijon simulations, groundwater table is 90% of the time deeper than 1.8 m and 2.1 m, respectively.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/9/C274/2012/hessd-9-C274-2012-supplement.pdf

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